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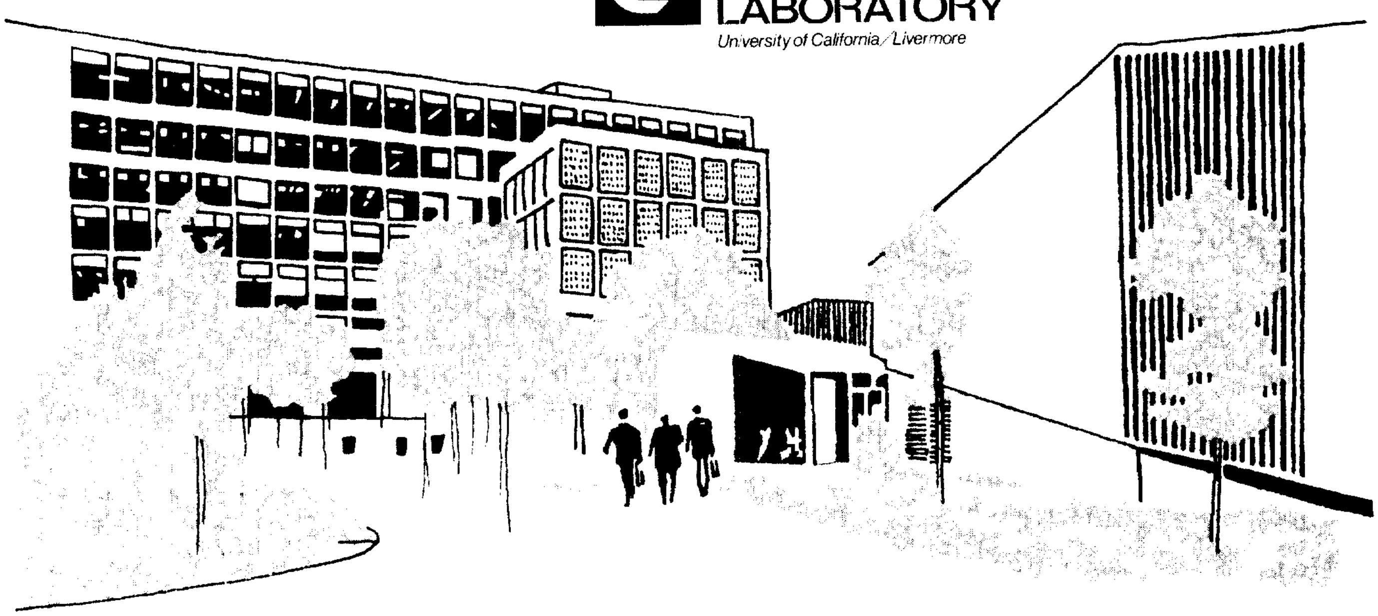

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Abstract

Source-strength measurements and environmental samples have been taken at the Humboldt Bay Nuclear Reactor site near Eureka, California, since mid-1971. We have used some of this data to evaluate the potential dose to man resulting from an aquatic release of radioactivity from the reactor. In this report, we provide an evaluation of individual and population dose through the marine pathways during 1972 and 1973 computed by the methods recommended by the U.S. Nuclear Regulatory Commission. During these years, individual adult exposure via the marine food chain totaled to a whole-body dose of 0.062 mrem/yr while teen and infant whole-body doses were even lower. Population dose to the whole body during this period was 0.121 person-rem/yr from sport fishing and 0.245 person-rem/yr from commercial fishing. These conservative estimations of dose rates are considerably lower than the USNRC recommended 3-mrem/yr limit to the whole body and 10-mrem/yr limit to any organ.

Introduction

Recently, the USNRC (U.S. Nuclear Regulatory Commission) issued guides to describe methods acceptable to the USNRC for implementing specific sections of the Commission's regulations. Most of our environmental data are presented in reports either published[1-4] or in preparation, but we have attempted to follow the USNRC guidelines in our evaluation of the existing data. In this report, we evaluate individual and population doses through marine pathways from gamma-emitting radionuclides released to the Humboldt Bay. Environmental data taken principally between mid-1971 through 1973 were used together with the methods for dose calculation as recommended in Appendices A and D of Regulatory Guide 1.109, "Calculation of Annual Dose to Man From Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR, Part 50, Appendix 1."[5] Following this guide, it is possible to identify areas (if any) in which we lack USNRC-acceptable, site-specific, environmental radiological data. Future environmental sampling programs at reactor sites will be planned with USNRC objectives in mind, taking any discovered deficiencies into special consideration. However, we emphasize that this method of reporting data does not represent, on our part, an endorsement of the computational methods suggested by the USNRC guidelines.

Description of the Site and Environmental Pathways

The Humboldt Bay power plant near Eureka, California, is operated by the Pacific Gas and Electric Company and produces electricity with two 54-MWe fossil-fuel units and one 65-MWe boiling-water reactor. Cooling water from the south end of the bay is pumped from an inlet canal, through the condensers of all three generating units and is discharged into a short canal that leads back to the central bay. Liquid radioactive wastes that are generated during reactor operations are accumulated in 7000-gal (2.7×10^4-ℓ) tanks. At irregular intervals, the accumulated radioactive liquid waste is processed to reduce the radioactivity levels, passed into the cooling water, and released to the discharge canal. Flow rates in the discharge canal vary between 2.8×10^8 and 5.6×10^8 ℓ/d. The activity is significantly diluted as the discharged radionuclides are transported to the center bay (see Fig. 1). Advective processes carry the radionuclides, either in soluble or particulate forms, through the bay environment and into the open ocean.

The regulatory guide considers radiation doses from two liquid effluent pathways, ingestion and shoreline deposits. Exposures through potable water, aquatic foods, and terrestrial foods irrigated with contaminated water are ingestion subpathways. The liquid effluent from the Humboldt reactor is discharged directly into marine water and thus, potable water and foods from contaminated irrigation areas contribute no dose to individuals and are not applicable subpathways at this site. No beaches in the bay are used for recreational purposes and so, exposure from shoreline deposits is of minor significance. However, some clams are taken by individuals from tidal flats during low tides. We attempt to

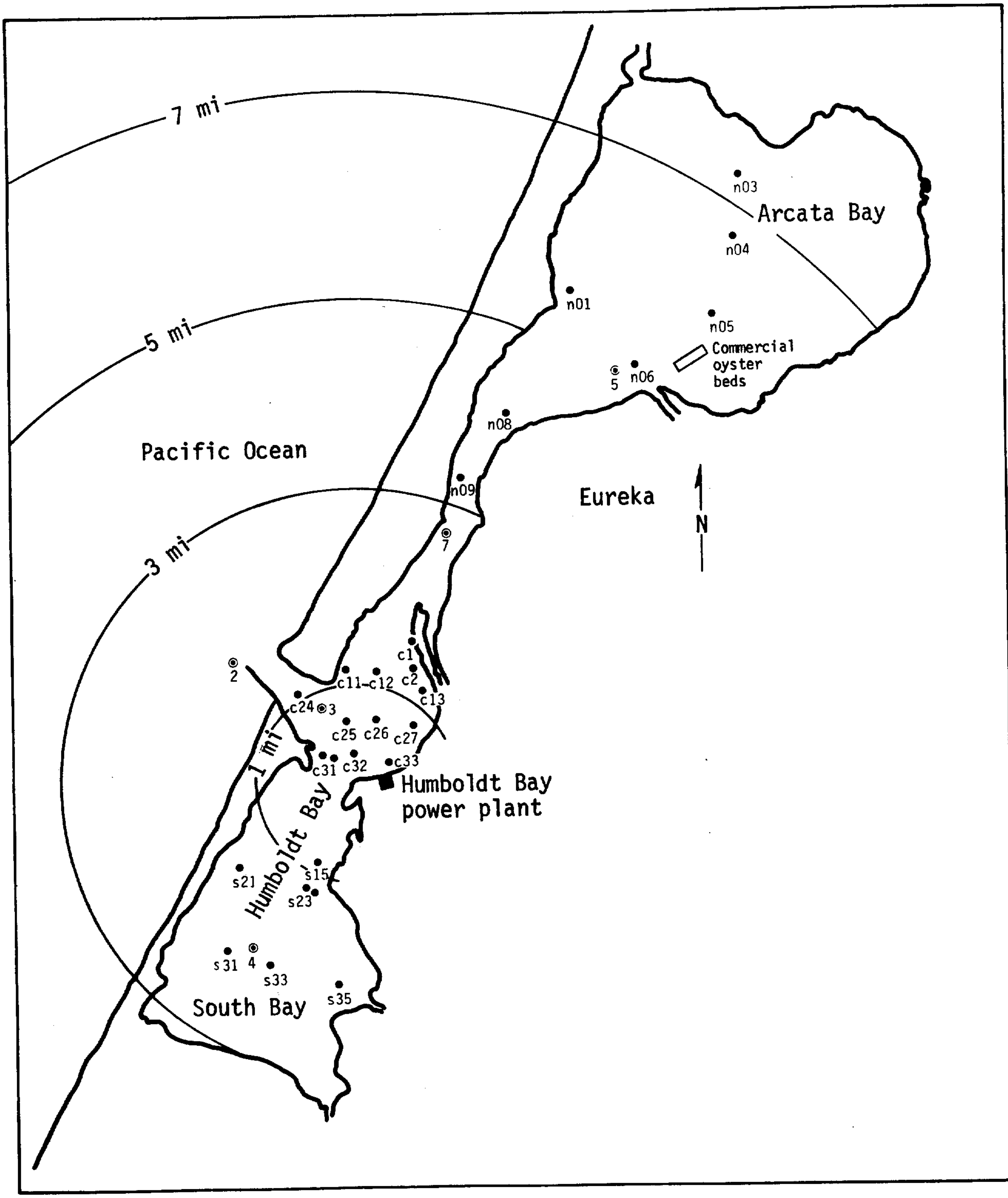

Fig. 1. Humboldt Bay area showing locations of the power plant in the central bay, the commercial oyster beds in the north bay, and the sediment and water sampling stations in the three bays. Radial distances from the power plant source are also shown.

evaluate the contribution of external dose from this activity. Organisms indiginous to the bay may concentrate some of the discharged radionuclides and pass them up the food chain to man. The major route to man at the Humboldt Bay is from consumption of these aquatic foods which include fish and invertebrates, principally the giant Pacific oyster.

Calculation of Annual Individual Dose

The USNRC maintains that dose to the whole body from all liquid effluent pathways should not exceed 3 mrem/yr/unit and that dose to any organ from all liquid effluent pathways should not exceed 10 mrem/yr/unit. Equation (1) from Ref. 5 is the fundamental equation recommended for calculating the radiation dose to man via liquid effluent pathways. Thus, R_{aipj}, the annual dose to organ j of an individual of age a from radionuclide i via pathway p in mrem/yr is calculated as follows:

$$R_{aipj} = C_{ip}\ U_{ap}\ D_{aipj}\ , \qquad (1)$$

where C_{ip} is the concentration of nuclide i in the media of pathway p in pCi/kg; U_{ap} is the intake rate or usage value associated with pathway p for age group a in kg/yr; and D_{aipj} is the specific dose factor for i, p, j, and a in mrem/pCi.

The USNRC recommends that concentrations in the environmental media (e.g., fish and invertebrates) should be evaluated for a high-velocity surface discharge at the edge of the initial mixing zone, where the effluent undergoes prompt dilution near the surface or, this location should be one that has been occupied during the power plant lifetime and it should be evaluated with respect to potential land and water usage as well as to food pathways that could exist during the term of plant operation. Unfortunately at Humboldt Bay, few if any of the major food organisms are found at the edge of the initial mixing zone. Over the better part of a 2-yr period, we obtained oysters to be analyzed for radionuclide content from the commercial beds in north Humboldt Bay. Clams, crabs, and English sole were randomly collected during the same period from other permanent locations in the bay for analysis. We calculated dose rates to man from the measured radionuclide concentrations in these food organisms.

When site-specific data are unavailable, the usage values U_{ap} given in Ref. 5 (abstracted in Table 1) are acceptable to the USNRC. However, Essig *et al.*[6] surveyed two Pacific coastal communities in 1970 and 1971 and found that seafood (e.g., oysters, clams, shrimp) was consumed at substantially different rates than those presented in Table 1. For example, during this period, adults in Rockaway, Oregon, consumed seafood at the rate of 12 to 28 kg/yr while the seafood consumption rate for adults in Ilwaco, Washington, was 25 to 40 kg/yr. Although this is not site-specific data, we have assumed that seafood consumption in a 50-mi radius of a Pacific coastal community such as Eureka, California, more closely resembles that of other Pacific coastal communities than that of the national average. For individual dose computations in this report, we assume that the entire catch is used at the highest rate of consumption listed in Table 1. A simple scaling factor can be used if computation of individual doses at the lower rates of consumption is desired.

Internal dose factors (D_{aipj}) are derived from those given by the International Commission on Radiological Protection (ICRP) for body burden. The dose factors for the

Table 1. Individual and per capita usage values U_{ap}.

Pathway	U_{ap} (kg wet weight/yr)		
	Child	Teen	Adult
Individual U_{ap}			
Fish[a] (salt or fresh)	6.9	16.0	21.0
Seafood[a]	1.7	3.8	5.0
Oysters[b]	7.6 ± 3.3	4.3 ± 1.7	8.3 ± 4.3
Clams[b]	5.8 ± 1.5	7.4 ± 2.9	10.3 ± 4.9
Crabmeat[b]	7.5 ± 9.6	4.8 ± 1.3	15.5 ± 13.1
Per capita U_{ap}			
Fish[a]	2.2	5.2	6.9
Seafood[a]	0.33	0.75	1.0

[a]Ref. (5).
[b]Ref. (6).

Table 2. Ingestion dose factors.

Radio-nuclide	Organ (mrem/pCi)					
	Whole body	Bone	Liver	Kidney	Lung	GI tract
Adult						
^{54}Mn	8.73 E-7	0	4.57 E-6	1.36 E-6	0	1.40 E-5
^{60}Co	4.72 E-6	0	2.15 E-6	0	0	4.02 E-5
^{65}Zn	6.97 E-6	4.85 E-6	1.54 E-5	1.03 E-5	0	9.70 E-6
^{134}Cs	1.21 E-4	6.22 E-5	1.48 E-4	4.80 E-5	1.59 E-5	2.59 E-6
^{137}Cs	7.15 E-5	7.98 E-5	1.09 E-4	3.71 E-5	1.23 E-5	2.10 E-6
^{144}Ce	2.62 E-8	4.89 E-7	2.04 E-7	1.21 E-7	0	1.65 E-4
Teen						
^{54}Mn	*[a]	*	*	*	*	*
^{60}Co	6.30 E-6	*	2.76 E-6	*	*	3.31 E-5
^{65}Zn	*	*	*	*	*	*
^{134}Cs	9.06 E-5	8.05 E-5	1.94 E-4	*	2.35 E-5	2.24 E-6
^{137}Cs	5.05 E-5	1.07 E-4	1.44 E-4	*	1.91 E-5	1.92 E-6
^{144}Ce	3.83 E-8	7.22 E-7	2.96 E-7	*	0	1.70 E-4
Child						
^{54}Mn	*	*	*	*	*	*
^{60}Co	1.55 E-5	*	5.17 E-6	*	0	2.86 E-5
^{65}Zn	*	*	*	*	*	*
^{134}Cs	8.02 E-5	2.24 E-4	3.77 E-4	*	4.19 E-5	2.04 E-6
^{137}Cs	4.50 E-5	3.12 E-4	3.02 E-4	*	3.54 E-5	1.84 E-6
^{144}Ce	1.14 E-7	2.14 E-6	6.70 E-7	*	0	1.74 E-4

[a] Use adult dose factors.

principal radionuclides released to the Humboldt Bay marine environment are abstracted from the values presented in Ref. 5 and are listed in Table 2.

The principal gamma-emitting radionuclides released from the Humboldt Reactor to the bay in 1972 and 1973 were determined from analysis of samples from the waste tanks provided by PG&E. The complete 1972 inventory is shown in Table 3 along with the major radionuclides that were present in the waste during 1973.[7] The cumulative values in Table 3 show only the source intensity during specific intervals of the study and define the principal radionuclides released to the aquatic environment. We make no attempt in this paper to describe the variability in radionuclide concentration released during these yearly intervals.

If the concentrations of the radionuclides in aquatic foods are unavailable, the following equation is accepted by the USNRC for calculating the individual dose (mrem/yr) from consumption of aquatic foods:

Table 3. Levels of gamma-emitting radionuclides released from the Humboldt Bay Reactor during 1972 (1973).[7]

Radionuclide	mCi/yr	
^{137}Cs	349	(874)
^{134}Cs	189	(621)
^{65}Zn	86.2	(84)
^{60}Co	28.4	(127)
^{54}Mn	16.8	(74)
^{51}Cr	13.6	
^{140}Ba	4.4	
^{144}Ce	4.2	(12)
^{106}Ru	3.5	
^{141}Ce	3.4	
^{59}Fe	3.1	
^{95}Nb	2.3	
^{95}Zr	1.6	
^{58}Co	1.1	
^{110}Ag	0.9	

$$R_{aipj} = (1100\ U_{ap}\ M_p/F) \times \sum_i Q'_i\ B_{ip}\ D_{aipj}\ e^{-\lambda_i t_p}\ . \quad (2)$$

In addition to the parameters defined in Eq. (1), M_p is the mixing ratio (the reciprocal of the dilution factor), F is the flow rate of the liquid effluent in ft^3/sec, Q'_i is the release rate of radionuclide i in Ci/yr, B_{ip} is the equilibrium bioaccumulation factor for nuclide i in pathway p, t_p (for internal dose) is the total time in hours elapsed between release and ingestion, 1100 is the conversion factor from Ci/yr per ft^3/sec to pCi/ℓ, and λ_i is the radiological decay constant of nuclide i in hr^{-1}. Therefore, the expression $(M_p\ Q'_i/F)e^{-\lambda_i t_p}$ is the concentration of radionuclide i at the time the product is consumed. The Q_i'/F term defines the concentration of nuclide i in the effluent at the point of discharge.

Calculation of Annual Population-Integrated Dose

We use the equations from Appendix D of Ref. 5 to compute dose to populations from the consumption of aquatic food products. For all aquatic food produced within the 50-mi radius of the plant, USNRC recommends that the radionuclide concentrations be averaged over the entire area by weighting the concentrations in each subregion according to the amount of food produced. This 50-mi average concentration $\overline{C}_{ip}$ of nuclide i in food p is given by

$$\overline{C}_{ip} = (1/V_p)e^{-\lambda_i t_p} C_{dip} V_{dp} , \qquad (3)$$

where t_p is the transport time of food p through the distribution system in days, C_{dip} is the average concentration over subregion d in pCi/kg, and V_{dp} is the annual mass of food p produced in the subregion in kilograms.

We have identified two aquatic subregions around the Humboldt Bay plant. The first subregion d_1 includes the marine area enclosed by a 7-mi radius from the plant. This area includes the commercial oyster fishery in the north bay (see Fig. 1) and the region from which radiological data is available for indigenous fish and invertebrates. The majority of sport fish are also taken within this area.

The second subregion d_2 includes the marine region bounded by the 7- and 50-mi radii. The limits of the radial distance extend from the town of Klamath, California, north of Eureka, to the coastal region west of Richardson Grove, California, south of Eureka. The mean depth of the Pacific Ocean enclosed by subregion d_2 is estimated at 1000 m. Subregion d_2 thus contains roughly 3×10^{13} m^3 of seawater. Reactor-generated radionuclides in food taken from subregion d_2 contribute a very insignificant dose to individuals. If the entire yearly inventory (Table 3) were conveyed to the open ocean, mixed, and retained in subregion d_2, the radionuclide concentration in the water of this region would be a fraction of an attocurie (10^{-18} Ci) per liter.

On several occasions following a release of radionuclides from the plant, 50-ℓ water samples were taken for analysis at stations close to the plant and from stations 1 to 5 mi from the plant. At radial distances greater than 1 mi from the plant, only ^{137}Cs and occasionally ^{134}Cs (the two radionuclides in highest concentration in the discharged waste) were detected after radiochemical separation from the water samples. The ^{137}Cs levels outside the 1-mi distance are only slightly above the worldwide fallout levels in surface ocean waters during the respective periods. Concentrations of ^{137}Cs and ^{134}Cs in samples from stations in Humboldt Bay are given in Table 4. For comparison, concentrations of ^{137}Cs in oceanic surface waters resulting only from worldwide fallout are shown in Table 5. (The stations identified in Table 4 are located for reference in Fig. 1.)

Within the 1-mi radius, elevated concentrations of ^{134}Cs and ^{137}Cs are noted in the water column following radionuclide releases from the plant. In the 50-ℓ water samples taken in the bay at a distance greater than 1 mi from the plant, ^{65}Zn, ^{60}Co, and ^{54}Mn were never detected at levels greater than 0.05 pCi/ℓ. Tidal mixing and dilution quickly reduce a concentration of 0.05 pCi/ℓ at the 1-mi distance to yet smaller concentrations at distances of 1 to 50 mi from the site boundary. Therefore, using the bioaccumulation factor B_{ip}

Table 4. Concentrations of ^{137}Cs and ^{134}Cs in Humboldt Bay and, for comparison, the concentrations of ^{137}Cs in prior releases from the plant.

Station No.	Sampling date	Sample concentration (pCi/1) ^{137}Cs	Sample concentration (pCi/1) ^{134}Cs	Prior release date	Prior release concentration (mCi) ^{137}Cs
2	6/14/72	0.27 ± 0.01	<0.01	6/13/72	15.5
3	8/3/72	0.36 ± 0.04	<0.02	8/2/72	1.3
4	8/2/72	0.32 ± 0.06	0.07 ± 0.03	8/2/72	1.3
5	8/3/72	0.31 ± 0.05	0.06 ± 0.02	8/2/72	1.3
3	4/5/73	0.25 ± 0.4	<0.02	4/4/73	22.1
4	4/5/73	0.17 ± 0.02	0.02 ± 0.01	4/4/73	22.1
7	4/5/73	0.17 ± 0.02	0.03 ± 0.01	4/4/73	22.1
3	7/31 to 8/2/73	0.19 ± 0.09	<0.01	7/31/73	17.5
7	7/31-8/2/73	0.15 ± 0.02	<0.01	7/31/73	17.5

Table 5. Oceanic surface concentrations of ^{137}Cs in 1972-1973 from world-wide fallout.

Location	Sampling date	^{137}Cs Concentration (pCi/l)	Reference
32°N 120°W	9/29/73	0.27 ± 0.13	8
31°N 130°W	10/1/72	0.43 ± 0.11	8
41°07'N 70°50'W	7/72	0.18 ± 0.01	9
41°07'N 70°50'W	11/72	0.17 ± 0.01	9
23-27°N 86-95°W	2/73	0.11 ± 0.01	Author's (VEN) unpublished data; average of 11 surface samples.

concept, the radioactivity levels in fish from region d_2 are indistinguishable from background levels and have no influence on the total individual dose from the Humboldt reactor. As a result, although we recognize pathway d_2, we will not consider it further in individual or population dose calculations.

In Eq. (3), V_{dp} is the annual mass of food medium p in kilograms produced in subregion d_1. The oyster fishery in north Humboldt Bay, approximately 6 to 7 mi from the reactor (see Fig. 1), dominates commercial seafood production in the region. During 1972, the oyster production was 3.41×10^5 kg and during 1973, the oyster production was 2.57 $\times 10^5$ kg, representing 0.5 to 1.5% of the total U.S. oyster harvest during these years.[10-12]

For the years 1972-1973, party boat records[11] for catches brought into Eureka and Fields Landing place the annual average number of fish at 3400. Not all or even a majority of these fish are caught in the bay. Indeed, it is quite probable that most were taken in the ocean within the 7-mi radius from the plant. Salmon was the major fish taken with an average sport salmon weight of 7.5 lb (3.4 kg) for an estimated average total mass of 11.6×10^3 kg (Refs. 11, 13, 14). Six to eight times this amount is reported to have been caught from small, private skiffs.[11] Thus, summing all catches for this period of time, it is estimated that 8.0×10^4 kg of fish, mainly salmon, is landed yearly from the area inside the 7-mi radius.

The radionuclide concentrations measured in the English sole caught in the bay are taken as representative of the concentrations in the entire fish catch. This assumes all fish have the same bioaccumulation factor which, without more site-specific data, is an acceptable assumption according to USNRC guides.[5]

This calculation of fish catch and consumption yields a conservative estimate of radionuclide concentration that maximizes the potential dose via the fish pathway. Dilution of the radionuclide concentrations greater than that anticipated within the 7-mi radius obviously occurs in the ocean at distances beyond the 7-mi limit where salmon mainly feed. Salmon do not feed after they migrate into the bay. Finally, the number of fish actually caught for consumption inside the bay (the region where we have radiological data) is a very small fraction of the reported total catch.[13]

Other invertebrates (e.g., clams, crabs) collected near Eureka from the local bay environment total no more than 10^4 kg or 5% of the annual oyster harvest. The remaining commercial catch brought into Humboldt Bay is taken from the open Pacific Ocean.

In Eq. (3), we defined V_p as the annual mass of food p in kilograms produced within the 50-mi radius from the Humboldt reactor. The magnitude of V_p differs for sport and commercial usage. For sport harvests, the entire edible harvest is assumed to be ingested by the population of the surrounding 50 mi. The population P_p served by all the food produced within the 50-mi radius is estimated by

$$P_p = V_p / \sum_a U_{ap} f_a , \qquad (4)$$

where U_{ap} is the per capita usage value for a specific age group a as recommended by the NRC guidelines (see Table 1) and f_a is the fraction of the population within the given age group.

For commercial harvests, the production within 50 mi of the site is considered as part of the total U.S. harvest. Equation (3) should be used to compute the average concentration with V_p defined as the total estimated U.S. commercial harvest of the aquatic food p. We can compute the annual population-integrated dose from Eq. (5) with $P_p = P_{50}$. The only commercial harvest we consider are the oysters. The fish and other invertebrates taken from subregion d_1 are all considered sport harvest. The annual population-integrated dose D_j^p is then

$$D_j^p = 0.001 \sum_p P_p \sum_i \sum_a \times f_a \overline{C}_{ip} U_{ap} DF_{ai} , \qquad (5)$$

where DF_{ai} is the dose factor for age group a and radionuclide i. This dose factor has the same values as D_{aipj} (Table 2). When calculating D^p_j, the current age distribution of the population within the 50-mi radius may be assumed to be the same as the current age distribution for the entire U.S. population.

English sole, crabs, clams, and oysters were obtained in specific months during 1972 and 1973 from the Humboldt Bay. The oysters were obtained from the commercial suppliers in north Humboldt Bay (see Fig. 1). The crabs, sole, and clams were collected from regions of south, center, and north bay by Humboldt State University students. Table 6 presents the measured radionuclide concentrations[7] in monthly composite samples and, for reference, the monthly quantity of the specific radionuclide that was released from the reactor. More often than not, in the organisms analyzed, many of the principal radionuclides such as ^{134}Cs were below detection limits. For these cases, the upper limit of detection (at the 95% confidence level) of the radionuclide in the sample was taken. No other reactor-produced radionuclides were detected by gamma spectrometry in these organisms. For the purpose of this assessment, we treat all upper limits as positive values when averaging concentrations.

This procedure again leads to an elevated estimate of the potential dose via the marine food chains. For example, ^{134}Cs was never detected in the fish, oysters, or clams and could be present in the tissues at levels considerably below the limits of detection. However, when the ^{134}Cs detection-limit concentrations are used, the predicted dose is equivalent to the dose from ^{137}Cs. In addition, because the ^{137}Cs concentrations measured in oysters, clams, and fish are not corrected for background fallout concentrations naturally present in the environment. Therefore, the ^{137}Cs doses calculated from these values and attributed to reactor operation are very conservative and yield upper-limit estimates for the predicted dose.

Because of the very low concentrations found in the food organisms and the somewhat limited sampling, no obvious comparisons of concentration levels with releases or time are evident in the data. The concentrations of the individual radionuclides most often detected in the organisms are averaged for the entire sampling period. These average values (Table 7) are the C_{ip} terms to be used with Eq. (1) for computing annual individual dose rates and are also the C_{dip} values to be used with Eqs. (3) and (5) for computing annual population dose rates. The U.S. population age distributions are abstracted from Ref. (12) and are presented in Table 8.

Table 6. Radionuclide concentrations in Humboldt Bay marine organisms.

Date	Monthly plant release (mCi)	Radionuclide concentration (pCi/kg wet weight)			
		Oyster	Clam	English sole	Crab
^{65}Zn					
1/72	0.90	—[a]	—	—	—
2/72	0.22	—	<50	—	—
3/72	0.08	—	<20	—	—
4/72	0.27	—	—	—	—
5/72	0.37	—	<10	<30	<30
6/72	0.51	—	<20	—	<30
7/72	0.75	—	—	—	<30
8/72	0.88	39	<20	<30	<60
9/72	4.03	—	—	<20	<20
10/72	63.9	17	87	25	32
11/72	13.2	22	106	105	29
12/72	1.19	100	67	—	—
1/73	4.02	95	69	—	<30
2/73	10.2	67	47	—	—
3/73	1.14	80	23	—	38
4/73	0.99	91	104	—	56
5/73	21.6	120	—	86	—
6/73	5.67	—	—	—	—
7/73	3.58	—	—	—	—
8/73	4.94	47	—	—	—
9/73	8.23	67	—	—	—
10/73	6.41	90	—	—	—
11/73	16.8	58	—	—	—
12/73	0.25	46	—	—	—
	mean	67 ± 31	52 ± 34	50 ± 36	36 ± 13
^{137}Cs					
1/72	6.13	—	—	—	—
2/72	1.47	—	15	—	—
3/72	10.1	—	5	—	—
4/72	15.0	—	—	—	—

Table 6 (continued)

Date	Monthly plant release (mCi)	Radionuclide concentration (pCi/kg wet weight)			
		Oyster	Clam	English sole	Crab
5/72	4.45	—	3	6	5
6/72	15.5	—	2	—	<3
7/72	2.32	—	—	—	<3
8/72	48.4	4	2	10	<6
9/72	18.9	—	—	11	<2
10/72	92.6	3	5	11	<2
11/72	105.1	3	6	9	<1
12/72	29.6	2	4	—	—
1/73	33.9	4	3	—	9
2/73	61.5	2	8	—	—
3/73	26.8	3	4	—	5
4/73	30.3	3	6	—	3
5/73	105.2	5	—	9	—
6/73	29.9	—	—	—	—
7/73	23.2	—	—	—	—
8/73	2.88	2	—	—	—
9/73	84.2	2	—	—	—
10/73	142.6	4	—	—	—
11/73	294.2	3	—	—	—
12/73	38.9	3	—	—	—
	mean	3 ± 1	5 ± 4	9 ± 2	4 ± 2
^{60}Co					
1/72	1.08	—	—	—	—
2/72	0.34	—	<50	—	—
3/72	0.20	—	<4	—	—
4/72	1.05	—	—	—	—
5/72	0.59	—	<30	<5	<6
6/72	0.59	—	<7	—	<6
7/72	0.71	—	—	—	<5
8/72	1.59	<2	<4	<5	<6
9/72	2.58	—	—	<5	<5
10/72	15.69	<1	<5	<5	<4

Table 6 (continued)

Date	Monthly plant release (mCi)	Radionuclide concentration (pCi/kg wet weight)			
		Oyster	Clam	English sole	Crab
11/72	2.96	<1	<5	<8	<2
12/72	1.20	<2	<5	—	—
1/73	3.12	<1	5	—	<5
2/73	8.82	<1	4	—	<5
3/73	0.65	<1	<2	—	<2
4/73	0.63	<1	<3	—	<4
5/73	7.04	<1	—	<6	—
6/73	1.81	—	—	—	—
7/73	1.59	—	—	—	—
8/73	5.30	<1	—	—	—
9/73	18.32	<1	—	—	—
10/73	15.21	<1	—	—	—
11/73	63.30	<1	—	—	—
12/73	0.77	<1	—	—	—
	mean	<2	<10	<6	<5
^{54}Mn					
1/72	0.17	—	—	—	—
2/72	0.06	—	20	—	—
3/72	0.10	—	7	—	—
4/72	0.28	—	—	—	—
5/72	0.07	—	6	9	<8
6/72	0.42	—	<5	—	<8
7/72	0.08	—	—	—	<7
8/72	0.70	<2	<4	7	<9
9/72	2.45	—	—	12	<5
10/72	10.39	<2	7	8	4
11/72	1.32	<1	10	16	<2
12/72	0.81	<2	6	—	—
1/73	2.01	<5	6	—	<9
2/73	3.98	<1	4	—	—
3/73	0.29	<1	<10	—	11
4/73	0.18	<1	5	—	4

Table 6 (continued)

Date	Monthly plant release (mCi)	Radionuclide concentration (pCi/kg wet weight) Oyster	Clam	English sole	Crab
5/73	0.59	<1	—	8	—
6/73	0.19	—	—	—	—
7/73	0.37	—	—	—	—
8/73	2.66	<1	—	—	—
9/73	9.90	<1	—	—	—
10/73	11.18	<1	—	—	—
11/73	41.72	<1	—	—	—
12/73	0.52	<1	—	—	—
	mean	<4	8 ± 4	10 ± 3	7 ± 3

[a]Dash indicates no sample taken.

Table 7. Mean radionuclide concentrations in Humboldt Bay organisms during the 2-yr (1972-1973) sampling period.

Radionuclide	Concentration (pCi/kg wet weight) Oyster	Clam	English sole	Crab
^{54}Mn	<4	8 ± 4	10 ± 3	7 ± 2
^{60}Co	<2	<10	<6	<5
^{65}Zn	67 ± 31	52 ± 34	50 ± 36	36 ± 13
^{134}Cs	<1	<3	<3	<3
^{137}Cs	3 ± 1	5 ± 4	9 ± 2	4 ± 2
^{144}Ce	<5	<30	<35	<45

Table 8. United States population age-distribution as of July 1, 1974.[12]

	Child 23.8%		Teen 8.0%	Adult (68.2%)			
Age (yr)	Under 5	5-13	14-17	18-20	21-44	45-64	Over 65
No. persons (10^6)	16.304	34.082	16.876	12.135	66.857	43.320	21.815

Computation of Dose from Humbolt Bay Commercial and Sport Aquatic Foods

Using Tables 1, 2, and 7, the annual dose R_{aipj} contributed by nuclide i to organ j for adults age a from the seafood ingestion pathway p is detailed in Table 9. In Table 10, the total whole-body and organ annual dose rates to adults, teens, and children are summarized for the seafood-ingestion pathway. The dose rates for the latter two groups were also obtained from the data in Tables 1, 2, and 7. Detailed tables similar to Table 9 were constructed for each age group but, for brevity's sake, they are not included in this report.

An inspection of Table 10 reveals that the dose rates for all age groups are well below the recommended maximum whole body dose of 3 mrem/yr/unit and dose to any organ of 10 mrem/yr/unit even though we made assumptions that yielded values that overestimate the actual dose from the reactor-produced radionuclides.

Using Eqs. (3-5) and the data presented in the previous sections of this report, we have evaluated the annual population-integrated total body dose from the consumption of aquatic foods using the sport and commercial harvests in subregion d_1 and the intake values in Table 1. These dose values are summarized as follows. For sport harvests, consumption of fish contributes 0.111 person-rem/yr and consumption of shellfish contributes 0.010 person-rem/yr for a total sport dose of 0.121 person-rem/yr. Because oysters are the only commercial harvest from subregion d_1, the total commercial dose contribution from consumption of these shellfish is 0.245 person-rem/yr.

External Radiation Dose Rate from Marine Sediments

Although methods to assess this specific pathway are not defined in the guidelines, individuals collecting clams and other invertebrates from tidal flats during low tides do receive an additional external body

Table 9. Adult annual dose R_{aipj} values for consumption of marine food products.

Radio-nuclide	Average value of $C_{ip} \times U_{ap}$ (pCi/yr)	R_{aipj} (10^{-3} mrem/yr)					
		Whole body	Bone	Liver	Kidney	Lung	GI tract
Fish consumption (U_{ap} = 21 kg/yr)							
^{54}Mn	210	0.2	0.0	1.0	0.3	0.0	2.9
^{60}Co	126	<0.6	0.0	<0.3	0.0	0.0	<5.0
^{65}Zn	1050	7.3	5.1	16.1	10.8	0.0	10.1
^{134}Cs	63	<7.6	<3.9	<9.3	<3.0	<1.0	<0.2
^{137}Cs	189	13.5	15.1	20.6	7.0	2.3	0.4
^{144}Ce	735	0.0	<0.4	<0.1	<0.1	0.0	<121
Seafood consumption[a]							
^{54}Mn	224	0.2	0.0	1.0	0.3	0.0	3.1
^{60}Co	197	<0.9	0.0	<0.4	0.0	0.0	<7.9
^{65}Zn	1650	11.5	8.0	25.4	16.9	0.0	16.0
^{134}Cs	86	<10.4	<5.3	<12.7	<4.1	<1.4	<0.2
^{137}Cs	138	10.0	11.0	15.0	5.1	1.7	0.3
^{144}Ce	1000	<0.0	<0.5	<0.2	<0.1	<0.0	<165

[a]The average C_{ip} values for oysters, clams, and crabs from Table 7 are multiplied by the appropriate individual U_{ap} from Table 1 and summed to arrive at the values listed for the specific radionuclides.

and skin dose as a result of reactor operation. According to the USNRC guidelines, any additional pathway is considered significant if a conservative evaluation of the pathway yields an additional dose contribution equal to or greater than 10% of the total dose from all other pathways described in the guide.[5]

This dose rate can be computed directly from Eq. (1) if the sediment concentrations of radionuclide i are

Table 10. Total dose to designated organ from consumption of marine food products.

Age group	Organ (10^{-3} mrem/yr)					
	Whole body	Bone	Liver	Kidney	Lung	GI tract
Fish						
Adult	29	25	47	21	3	140
Teen	18	24	43	16	4	108
Child	8	26	33	7	3	48
Seafood						
Adult	33	25	55	27	3	192
Teen	15	17	34	14	2	86
Child	17	43	61	17	5	110
Total						
Adult	62	50	102	48	6	330
Teen	33	41	77	30	6	194
Child	25	69	94	24	8	158

available with appropriate external dose factors and usage values or period of yearly exposure.

During February 1973, a number of 10-cm deep core samples and 2.5-cm deep surface sediment sections were collected from north, center, and south bays. The core samples were taken from the locations identified by code number in Fig. 1 and in Table 11. All cores were sectioned into 2.5-cm increments. Each increment was prepared for gamma spectrometry analysis. The results for ^{137}Cs, ^{134}Cs, ^{54}Mn, and ^{60}Co, expressed in pCi/m^2 to a depth of 2.5 and 10 cm are abstracted from Ref. 7 and are presented in Table 11. All other radionuclides released to the bay from the Humboldt reactor were below limits of detection in the samples analyzed. The mean-surface concentration in the top 2.5 cm of sediment in each of the three bays are used for dose computation. Table 12 lists specific radionuclide external dose factors for an individual standing on contaminated ground.

The usage values or period of yearly exposure for this activity are not known. However, we can estimate the most probable highest values by assuming that, on the average, one low tide occurs each day during

Table 11. Radionuclide levels in Humboldt Bay sediment samples collected in February 1973 to a depth of 2.5 and 10 cm.[7]

Sample ID	Radioactivity level (10^{-3} pCi/m^2)							
	^{137}Cs		^{134}Cs		^{54}Mn		^{60}Co	
	2.5 cm	10 cm	2.5 cm	10 cm	2.5 cm	10 cm	2.5 cm	10 cm
Center bay								
c01	1.8	5.7	0.78	2.5	0.33	1.5	<0.3	<1.2
c12	0.96	4.5	0.68	2.3	0.38	1.3	<0.1	<1.5
c26	1.9	6.2	0.46	1.9	0.74	1.5	0.7	<1.4
c27	1.1	3.1	0.56	3.2	0.20	0.84	<0.2	<1.4
c33	1.7	3.7	0.56	2.6	0.44	0.69	<0.2	<1.4
c02	1.7		0.46		0.11		<0.2	<1.4
c24	0.94		0.54		0.23		<0.1	
c25	1.7		0.64		0.46		<0.1	
c31	3.1		0.38		0.50		<0.1	
c32	0.69		0.16		0.30		<0.4	
c11	0.53		0.11		0.15		<0.1	
c13	0.65		0.24		0.10		<0.1	
mean	1.4 ± 0.7	4.6 ± 1.3	0.46 ± 0.21	2.5 ± 0.5	0.33 ± 0.19	1.2 ± 0.4	<0.2	<1.4
North bay								
n01	9.0	41.8	0.53	2.9	0.1	0.54	<0.3	<1.2
n03	6.8	16.7	0.24	1.6	0.3	1.60	<0.2	<1.3
n04	8.9	33.2	0.80	2.6	0.41	1.65	0.7	<2.0
n05	7.9	36.5	0.69	2.6	0.77	1.72	1.1	<2.0
n06	10.3	33.8	0.52	2.5	0.54	1.06	<0.2	<1.3
n08	6.1	19.9	0.71	2.8	1.59	3.59	1.0	1.6
n09	5.6	23.2	0.25	2.3	0.54	2.08	0.3	<1.3
mean	7.8 ± 1.7	29.3 ± 9.4	0.53 ± 0.22	2.5 ± 0.4	0.61 ± 0.48	1.75 ± 0.95	0.5 ± 0.4	
South bay								
s15	5.7	22.0	0.51	2.2	1.6	3.6	1.6	2.0
s21	6.7	19.8	0.40	1.9	0.2	1.0	<0.2	<1.0
s23	5.7	23.9	0.66	2.2	0.5	2.5	0.4	1.2
s31	6.0	23.9	0.85	3.9	1.3	2.6	2.9	5.0
s33	7.5	24.2	0.42	2.3	1.1	2.4	1.1	2.1
s35	6.2	24.5	0.47	3.7	2.1	3.2	2.8	3.6
mean	6.3 ± 0.7	23.1 ± 1.8	0.55 ± 0.17	2.7 ± 0.9	1.1 ± 0.7	2.5 ± 0.9	1.5 ± 1.1	2.5 ± 1.5

daylight hours and that four months out of the year are suitable for clamming. A devoted clammer will only spend, on the average, 2 hr collecting during a low tide. The individual is thus exposed for an estimated 240 hr/yr. The total body and skin doses for external exposure in the three regions of Humboldt Bay are calculated from this estimation of yearly exposure and from the data in Tables 11 and 12 (see Table 13).

Because the collection of clams and invertebrates is strenuous, it is principally an adult activity and child and teen doses are not computed. This pathway contributes, at the most, and additional 25% of the adult whole-body dose above that received from the consumption of marine products from Humboldt Bay. The contribution to the population dose is very minor because of the small percentage of the population actually engaged in clamming at the bay.

Table 12. External dose factors for an individual standing on contaminated shore.

Radionuclide	Dose (10^{-9} mrem/hr per pCi/m^2) Whole body	Skin
^{54}Mn	5.80	6.80
^{60}Co	17.0	20.0
^{65}Zn	4.00	4.60
^{134}Cs	12.0	14.0
^{137}Cs	4.20	4.90

Table 13. Whole-body and skin[a] external dose at Humboldt Bay.

Radionuclide	Whole-body dose (10^{-3} mrem/yr) Center bay	North bay	South bay
^{54}Mn	0.5	0.8	1.5
^{60}Co	0.8	1.9	6.1
^{65}Zn	0.5	0.5	0.5
^{134}Cs	1.3	1.5	1.5
^{137}Cs	1.4	7.9	6.4
Total	4.5	12.6	16.0

[a]Skin dose in mrem/yr = 1.17 × whole-body dose rate.

Comparison of Dose Rates with Annual Releases

The reported total gross activity levels (curies) discharged in the liquid waste from the Humboldt Bay reactor site between 1967 and 1972 are listed in Table 14.[15] No reported data are available to us for the individual radionuclides released in these years except for 1970 where the sum of ^{134}Cs, ^{137}Cs, ^{65}Zn, ^{60}Co, and ^{54}Mn activities equaled the gross

Table 14. Gross annual radioactivity released from the Humboldt Reactor and estimated adult whole-body dose rates.

Year	Annual activity (Ci)	Estimated dose rate (mrem/yr)
1972-1973	1.23 ± 0.79[a]	0.062
1971	1.80	0.091
1970	2.40	0.121
1969	1.50	0.076
1968	3.20	0.161
1967	3.13	0.158
1966	2.34	0.118
1965	1.89	0.095
1964	0.66	0.033
1963	0.40[b]	0.020

[a]Measured values. Data for all other years is from Ref. (15).

[b]First year of reactor operation.

beta-gamma activity reported to have been released.[15]

As an approximation, we must assume that the principal radionuclides released from the plant in the early years were in roughly the same proportion found in the 1972 and 1973 discharges. We can estimate the dose rate to man during these early years of operation by assuming that the radionuclide concentrations in food were also proportional to the quantity released in any year and that individuals consumed marine foods at the rates given in Table 1. The average total activity discharged during 1972-1973 was 1.23 ± 0.79 Ci and the adult whole-body dose from fish and seafood during this period was 0.062 mrem/yr. These values yield an annual dose rate of 0.05 ± 0.03 mrem/yr per released Ci/yr. Multiplying this value by the curies released annually gives the adult whole-body dose rate for any operating year prior to 1973 (Table 14).

An inspection of Table 14 reveals that in no year since the Humboldt Bay reactor went into operation in 1963 has the estimated adult whole-body dose been greater than a few percent of the 3 mrem/yr guideline value.

Summary

The dominant marine pathway to man from aquatic releases of radionuclides from the Humboldt Bay Reactor is through the consumption of aquatic foods. The only other pathway identified at the bay affects only a small group of individuals who gather clams from the tidal flats during low tides. Following the USNRC recommendations for dose computation,[5] the computed external, adult whole-body dose rate from clamming is at most

25% of the annual dose rate from aquatic food consumption.

Using available radiological data for marine species and pathways plus the computational methods recommended by the USNRC,[5] during 1972 to 1973, the recommended limits of 3 mrem/yr to the whole body and 10 mrem/yr to any organ were not exceeded. Adult exposure via the marine food chain during this period amounted to a whole-body dose of 6.2×10^{-2} mrem/yr. Teen and child whole-body doses were even lower. Population dose to the whole body during this period was 0.121 person-rem/yr from sport fishing and 0.245 person-rem/yr from commercial fishing.

An extrapolation of the 1972-1973 concentrations and dose rates to any previous year of reactor operation yields the conclusion that the annual whole-body dose rate for adults consuming aquatic foods at Humboldt Bay has never exceeded the recommended limit of 3 mrem/yr.[5]

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